

ASSESSMENT OF CONCEPTS AND RESEARCH FOR COMMERCIAL-AVIATION FIRE-SAFE FUEL

Mr. Bernard Wright
Southwest Research Institute
P.O. Drawer 28510
San Antonio, TX 78228
210/522-2585

Dennis M. Zallen, Ph.D., P.E.
ZIA Engineering
14216 Turner Court NE
Albuquerque, NM 87123
505/299-3025

ABSTRACT

This paper presents the research for the study entitled "Assessment of Concepts and Research for Commercial-Aviation Fire-Safe Fuel". The study was directed at the assessment of concepts and research for fuel fire safety. The study was to (i) survey past and current efforts, (ii) identify innovative methods, (iii) define necessary research, and (iv) assess the implications of future designs and operations. Effort concentrated on post-crash fires with consideration for synergism to eliminate fire hazards of on-board stored fuel and spilled aviation liquid fuels. Results of information reviews and concepts to reduce fuel fire hazards are presented.

After describing the program, discussions of jet fuels and of aircraft fires are presented. The potential concepts for fire-safe fuel were organized into three categories: (1) MODIFIED-FUEL SUPPLIED TO AIRCRAFT, (2) MODIFIED-FUEL UPON CRASH DEMAND, and (3) AUTOMATIC RELEASE OF PROTECTION. Within these categories the following technical topics are presented and finally evaluated: GELLED JET FUEL, EMULSIFIED JET FUEL and Practical Applications of Gelled and Emulsified Fuel, VAPOR-PHASE INERTING EMULSIONS with Aqueous Fuel Emulsions and Suppressant Emulsions, ANTI-MISTING KEROSENE discussing AMK Research and Shear-Thinning Anti-Mist Agent, MODIFIED-FUEL UPON CRASH DEMAND, NON-VOLATILE PRECURSORS (NVP), SELF ACTIVATING POWDER EXTINGUISHMENT, ENCAPSULATION, PRE-BOARD ANTI-MIST OR ONBOARD GEL MODIFICATION, AUTOMATIC RELEASE OF PROTECTION, FUEL TANK PROTECTION, EGRESS PROTECTION, SOLID PROPELLANT GAS GENERATORS, and OTHER PROTECTION. The final discussion was a summary of findings with rated recommendations.

1.0 INTRODUCTION

A continuing hazard associated with aircraft is the fuel fire following a survivable crash. No methods have been successfully developed for protection against an external fuel fire immediately after aircraft crash ending. This is the most critical period since there is some time afterwards until ground crews can control the sustained fire to perform rescue. There is a need to identify and develop concepts for mitigation of a nearby external fire. The identification and

recommendation of potential concepts for commercial-aircraft fire-safe fuel is the work discussed in this paper.

Current designs of commercial and military aircraft incorporate a broad array of fire safety features. New requirements in the last decade have imposed stringent fire safety standards on civil aircraft, such as fire-resistant cabin lining materials, seat cushions, and liners for compartments. Design features of materials alone cannot protect aircraft against the danger of fire because burning fuel has dominated most post-crash fire scenarios and causes even the most fire-resistant materials to readily burn. Therefore, the reduction of the fire hazard of fuel is critical in improving survivability in post-crash fires.

Planning groups, called aviation safety investment strategy teams (ASIST), defined three program elements of safety monitoring, accident prevention, and accident mitigation. The ASIST planners identified three overall investment areas in the element of accident mitigation: fire prevention, systems approach to crashworthiness, and systems approach to evacuation. In-flight fires in aircraft, while very rare, are greatly feared. These fires threaten loss of control in flight and a resulting crash with little chance of escape. More common, however, are fires that occur from fuel spills after accidents, even in events with mild, survivable deceleration forces.

The Southwest Research Institute (SwRI) performed a critical review of concepts to improve the fire-safe performance of aviation fuels. The study emphasized applications to commercial transport aircraft and those improvements and modifications to reduce fuel-fire hazards in crash situations. In some cases, in-flight fire reduction has relevance to crash-fire reductions and this synergy was part of the review. Recommendations were made of further action for the support of fire-safe fuel.

Critical assessments were done of past studies on fuel flammability and of past efforts to reduce crash and in-flight fires. Existing data on fuel flammability, thermal properties and flow properties were reviewed. Critical assessments were done of possible concepts, tried and untried, for altering fuel phase and flow behavior, and of possible concepts for modifying fuel flammability. Possible concepts for fire barriers, inerting and other potential methods for fire-safe aviation fuel as they can be applied to commercial-airplane fire protection were generated.

2.0 FUELS AND BURNING

Fuels comprise a substantial portion of an aircraft's weight and are the major contribution to the total aircraft fire load. For example, one version of the Boeing 747-400 holds up to 57,285 gallons of fuel; this constitutes approximately 195 tons and almost one-half the takeoff weight.

Jet A and Jet A-1 are the fuels used by commercial aircraft and therefore are of primary interest for this study. Both fuels have a minimum flash point of 100°F but Jet A has a freeze point of -40°F whereas Jet A-1 has a freeze point of -53°F. Commercial fuels in the U.S. are not

required to contain antistatic additives. Most of the Jet A fuel used in the U.S. contains no additives. Outside the U.S. the civil jet fuel Jet A-1 contains up to 5 ppm of an additive to increase electrical conductivity, which increases the rate of dissipation of any electrostatic charge that may have built up in the fuel (Taylor, 1997). Antioxidants may also be added (up to 24 ppm) to prevent the formation of hydroperoxide and gum from free radical reactions involving dissolved oxygen. A metal deactivator is permitted (up to 5.7 ppm) to chelate dissolved metals such as copper. Chelation eliminates the deleterious catalytic effects of dissolved metals on fuel stability.

Liquid hydrocarbon fuel pools and droplets burn in the gas phase. Heat is transferred to the liquid to cause vaporization whereby the fuel diffuses to meet with oxygen to form a flammable gas mixture. Gelled fuels prevent burning by preventing enough fuel mist droplets and fuel vapor to form a flammable mixture. Emulsions with water prevent pool burning by the release of enough water from the liquid phase to the vapor phase at the flame front, and suppressant emulsions release a fire extinguishing agent at the flame front to prevent flame propagation, i.e., pool burning. Tests at SwRI has shown that although a fire suppression agent such as perfluorohexane (C_8F_{14}) may perform well when applied externally to extinguish a fire, it will not perform well as an inerting agent mixed with the fuel because its volatility is too low to provide enough concentration at the flame front to prevent pool burning. Antimisting agents perform by preventing enough fuel mist/droplets so that a flammable mixture cannot be formed, and thereby there will not be an ignition source of sufficient strength (intensity and duration) to ignite a liquid fuel pool.

The flammability limits of fuel mists are strongly influenced by the droplet size distribution of the dispersed liquid phase (Weatherford and Wright, 1975). In fact, on the basis of hydrocarbon weight per unit air volume, the lower flammability limit for mists can be less than that of the same hydrocarbon in a homogeneous vapor/air mixture. It is partly because of this latter phenomenon that fuel mists represent a significant flammability hazard even though their ignition energy is greater than that of gaseous fuels. It should be noted that mists also create a substantial hazard because they may be flammable even when the droplet temperatures are substantially lower than the flash point temperature of the fuel. This anomaly is caused partly by the fact that the vapor pressure of a liquid is significantly increased by surface tension effects. At the surface of each fuel drop the fuel vapor concentration varies from equilibrium (or dynamic) vapor pressure through a decreasing concentration range to zero in the bulk air surrounding the drop. Hence, if the equilibrium vapor pressure (as enhanced by surface tension) at the liquid droplet surface exceeds the lower limit of flammability, a flammable mixture may occur somewhere between the drop surface and the bulk air phase, irrespective of the weight concentration of fuel in air. Flames can propagate readily in such fuel mists unless the mist dispersion is too dilute to support combustion. This anomaly is differentiated from low Apparent@ lean limits of flammability of mists due to fuel droplet enrichment of the flame front due to sedimentation effects.

In another respect, fuel mists in air could be potentially more dangerous than pre-vaporized fuel in air. Flame propagation rates through fuel mists may be faster than through

vapor-phase fuel/air mixtures, to the extent depending upon the characteristics of the particular mist dispersion. This enhanced flame velocity of mists has been attributed to the presence of acetylene and hydrogen formed by pyrolysis in the thicker flame and increased expansion factor since the unburned mist dispersion being entered by the flame front would be accelerated more by flame-generated expansion than would the unburned mixture in the absence of mist.

It has been assumed that in a severe but survivable aircraft crash the aircraft would be damaged while still moving forward and that the fuel would leak from damaged tanks or lines into a high speed airstream. This would lead to the formation of a fine mist which could readily ignite, thereby covering large areas of the aircraft in a fireball. While the burning mist might last for a few tens of seconds it would inevitably ignite any major fuel spillage in the vicinity of the aircraft, thereby producing a longer lasting and therefore more destructive fire. It was argued (Miller, 1975) that three properties would be important in affecting the incidence of fire and subsequent evacuation of passengers and crew: (1) fuel mobility, (2) tendency to form mists, and (3) rate of flame spread over spilled fuel. Some work has been done on thickened fuels since fuels of this type should spill less readily from damaged aircraft. However, far greater amount of work has been devoted to fuels containing mist-suppressing additives. Although these antimist additives pose some problems it was felt that they would be more easily overcome than those arising from the use of thickened fuels. Fuels can be ignited through the vapor or through the mist and there is no point in suppressing mist formation in a volatile fuel where the former mechanism is possible. Mist-suppressing additives are therefore only of use in fuels which are below their flash points.

Explosion suppression systems, fuel tank foam/foil, and fuel tank inerting for preventing tank fires will be ineffective in accidents where major fuel tank rupture has occurred. In such cases, the major hazard is the external pool of burning fuel. Some degree of protection would be provided where minor damage occurs. Direct ignition of vapors in the tank by conduction of heat through the tank wall is unlikely for small fires. The fuel system must be designed and arranged to prevent the ignition of fuel vapor within the system by (a) direct lightning strikes to areas having a high probability of stroke attachment, (b) swept lightning strokes to areas where swept strokes are highly probable, and (c) corona and streaming at fuel vent outlets.

3.0 POTENTIAL CONCEPTS

Some past studies on fuel flammability, aircraft fires, and lack of data have been reviewed. These reviews indicate that: (a) data is needed about the time-temperature and fuel-quantity history of the fuels as well as the pressure/shear history aboard aircraft, (b) the unique problems of the aircraft crash fire make it essential that some protection be aboard, (c) cost-effectiveness and weight-effectiveness must be evaluated early, (d) additional time/protection for passenger evacuation via cabin water spray is desirable, (e) crash-worthy (containment) systems enhance fire-safety, and (f) comprehensive details about crash scenarios are needed (e.g., involvement and duration of hot surface ignition). Understanding a systems approach, the U.S. Army responded to the problem of inadequate containment which permits vaporization of large quantities of fuel by

improving containment and chemically altering the physical state of liquid fuel so that it will not atomize into a fine mist. AIn a controlled crash test of a C-45, impacting at 96 mph, behavior of polyurethane-bonded multi-ply nylon tanks was observed. The right wing impacted with a telephone pole, directly at the center of the tank, and compressed the outboard tank to almost fifty percent of the tank depth. The tank volume was dramatically rearranged, but the tank did not leak@ (McCourt, 1966). A somewhat similar material with a felt core and a surface of pleated thermoplastic film also worked extremely well.

The sufficient amount of detailed technical property and conditions data will need to be determined for the specific fire-safe-fuel technology. Specific data for neat and modified fuel will need to be determined; for example, fuel droplet size and droplet time-temperature history (vaporization and condensation) versus viscosity, density, and surface tension. Modified jet fuel does not usually behave as a liquid. The science of rheology (Kahn, et al, 1997) attempts to bridge the gap between solid mechanics (which deals with perfectly elastic solids) and fluid mechanics (which deals with perfectly viscous liquids). A modified fuel is a viscoelastic system that exhibits a combination of elastic and viscous behavior. Rheology is not an exact science and further developments may be needed to sufficiently characterize modified fuel formulation and trials.

Realistic and detailed airplane crash scenarios need to be established, and fuel system design criteria for improved fuel containment should be updated. The specific details needed to evaluate different fire-safety technologies may be different, but, in general, there remains many unknowns in absolute values for significant parameters, computational capabilities and testing techniques. For examples, (a) the shear due to engine exhaust should be evaluated, (b) modeling of atomization of fuel after release was not computationally possible, and (c) improved rheological tests can be developed as well as characterizing droplet ignition propensity.

The following summary and recommendation discussion was put into five categories according to the stage at which the jet fuel was made safer. These include methods for in-service protection as well as fire-safety upon a crash. Each technique or method is rated according to whether it is (Rating-1) a high priority for research and development (R&D), (Rating-2) a medium priority that definitely should be researched further for feasibility, (Rating-3) a medium priority for a method that works well toward fire safety but does not itself stand alone, (Rating-4) a high risk, and (Rating-5) not applicable.

3.1 PRE-IMPACT FUEL VAPOR MODIFICATION

For some time now the military has used with much success the methods of porous foam fillers in fuel tanks (C-130) and dry bays, inerting fuel tank ullages with halons (F-16) or nitrogen (AH-64), and explosion suppression systems (M-1). These well-developed methods, some operating to completion (detection and suppression) in 100-millisecond, are applicable for combat projectile protection but present limited capability toward the prevention of external fires caused by ignition of the fuel released from damaged fuel tanks under post-crash conditions. However, if

indeed there is a potential for an explosive fuel/air mixture to form in tank ullages due to heat input by ambient conditioning when standing at an airport or environmental control conditioners under fuel tanks, then these techniques (Rating-3) have direct applicability. Additionally, the great success for post-crash fuel-fire safety of the bladder fuel tanks in helicopters may have applicability (Rating-3).

Some basic data is needed to characterize the potential situations that can and do occur. Of most importance (Rating-1) is the time-temperature history of the fuel. From the moment the fuel is loaded there are various environmental factors that influence the temperature of the fuel, including the amount of fuel in each of the tanks. When standing, fuel loading, passenger loading, moving, takeoff, and landing, the fuel temperature can rise, dependent on the heat input and the amount of fuel in each tank. The amount of vapor release is important for flammability, but also the temperature cycling of the fuel must be known to characterize the behavior of additives. Since jet fuel is a mixture with a distillation curve, then the volatiles initially released may not necessarily be described as jet fuel but more likely the light-ends of the fuel.

Fuel tank ullage explosions have been noted in several aircraft accidents. Fuel vapor ignition with the resultant explosion is a catastrophic event. These can readily be prevented by several means such as fuel tank ullage venting of fuel vapors, inerting the ullage with gases, or inerting the fuel tank ullage only when needed, e.g., the polymer mat whereby inerting agent would only be released when needed (Rating-4). Although these techniques do not provide but some assistance to post-crash spill-fuel fire, they alone may prevent explosion and by-itself save the aircraft, if and when explosive vapors form in tank ullage (Rating-2).

Since it is the fuel mist generated under crash conditions that is of utmost importance, then further work is recommended (Rating-1) to describe the mist size distribution and ignition energies of the neat fuel as well as the changes in mist and ignition characteristics when the fuel is modified for fire-safety. The mechanics and resultant mist formation for realistic and detailed airplane crash and post-crash scenarios need to be established. Even though, at first glance, it may appear that the fuel left behind the aircraft may not play a role when the aircraft comes to rest, the fuel conditioned by the crash (vibration, dispersal, mist-formation) may have a significant impact on the post-crash fire scenario. That is, the fuel that has been ignited with flame-holding may act as an ignition source. Such data are also important for modeling of crash fuel dispersal and modeling post-crash scenarios. Such modeling (Rating-3) is also important as an addition to intuition. For example, let's say the primary fuel is protected with an anti-mist agent, the wing tanks are filled, and the center tank was not filled for use. Then sufficient protection is not afforded to the center tank because it has the potential for explosion via fuel vapor formation and inerting of the center tank is needed. Therefore, systems and operational analyses (Rating-1) must be accomplished to assist in defining sufficient and complete fire safety.

The contribution of other fluids, primarily lubricating oil and hydraulic fluid must be considered (Rating-3) in addition to the liquid jet fuel. The improvement afforded by the use of a lower volatility fuel should be evaluated, although the gains may be marginal for post-crash

scenarios. If fuel properties are changed to improve fire safety, other performance specifications might not be met; for example, decreasing the volatility of a fuel by raising the flash point temperature may interfere with engine relight capability and low temperature pumpability.

Various in-flight as well as post-crash concepts for fire-safe fuel usually consider the fuel mist and fuel vapor and use the fuel flash point temperature as characteristic for ignition. However, the autoignition temperature (AIT) is indicative of the lowest temperature of a hot surface to cause ignition of the fuel, and the AIT usually differs significantly from the flash point temperature. So, when hot surfaces are present then ignition by hot surfaces such as engine parts or hot brakes must be taken into account for fuel-fire safety. Similarly for complete analyses, other inducements such as jet engine exhaust causation of liquid fuel mists, engine induction system flames (surge), recirculation zones (temperature and gases), and flameholding surfaces must be included.

3.2 FUEL MODIFICATION PRIOR TO CRASH

Although it is realized that aircraft fuel tank geometry is somewhat complex, it is thought that perforated tubing could be implemented inside the various size and shape fuel tanks. The Abrams Tank uses aluminum tubing bent at various angles with drilled holes along the different lengths of tubing to distribute its halon protection. It seems likely that such a distribution system could be employed in aircraft fuel tanks for rapid distribution and mixing of a halon-type inerting agent. Two concerns arise for this relatively easy and proven fire-safe fuel concept: (1) halon-type substances are indeed available (Zallen, 1994) for the appropriate volatility but unlike their volume-percentage efficiency, the halons are relatively heavy so their weight-effectiveness may not be optimal, and (2) enough halon must be carried aboard the aircraft upon takeoff to be able to inert all the fuel loaded on takeoff and this is a weighty concept (Rating-4). Although halon has been used for fuel tank ullage inerting it has never been implemented at full-scale for making fire-safe all the fuel aboard an aircraft.

An unproven concept that holds promise is the addition of small amounts of inexpensive non-toxic cyclododecylamine (CDDN) which can be dissolved easily and quickly into jet fuel. The solution remains completely fluid until carbon dioxide is added in small amounts. With carbon dioxide addition, a reaction takes place instantly (2 sec) to form a zwitterionic carbamate with complete gelation of the fuel. All the fuel on-board would be blended at the refinery with the CDDN agent. The dissolved agent does not separate and there are no changes in the fuel characteristics until gelation is effected. The agent is compatible with water and no in-flight degrading system is required. Later at a time of impending crash, the carbon dioxide would be added to the fuel tanks to cause the fuel to gel (Rating-2). Carbon dioxide addition could be done with aluminum tubing bent at various angles with drilled holes, as mentioned above for distributing halon. Gellation had been achieved with 2% CDDN and 0.2% glycol ether accelerator.

When lower concentrations of CDDN are blended with the fuel, the anti-misting effects

displayed by conventional AMK agents are noted. At concentrations below capability for complete gelation the scenario changes considerably. Now the agent would be both blended with the fuel and also carbonated at the refinery. Thus, the crew would not have to activate the system, there would be no reaction time involved, and the agent would be an effective countermeasure for all crash scenarios (Rating-2).

It was mentioned above that halon could be used to make all the jet fuel fire-safe. One of the problems with putting halon in a fuel occurs when the fuel is then burned in the engine; that is, corrosive products are formed in the burning process. (The high pressure/temperature conditions of a turbine engine allow the fuel to be burned whereas it would not burn at normal conditions.) In order to have the halon-type fire suppressing agent available to inert the fuel yet not be burned in the jet engines the concept of micro-encapsulating the halon allows the halon to be separated before the fuel goes into the jet engine. In this mode the halon-type capsules would be activated upon contact with fire to release the inerting agent (Rating-4). The other, more controllable concept, was to cause degradation of the capsule outer shell to release the inerting agent by the addition of another chemical, using a distribution method similar to the addition of halon-replacements mentioned earlier (Rating-4).

Non-Volatile Precursors (NVP) are liquid chemicals whereby volatile agents, having high fire extinguishing capabilities yet undesirable environmental properties when used as-is, are derived by pyrolysis of non-volatile precursors upon exposure to heat in fire zones (Bannister, 1993). The NVP itself is not an high-efficiency extinguishing agent but also does not present undesirable environmental concerns. Not only could the NVP agents be used to replace the current Halon-1301 agent aboard most aircraft for engine fire protection (Rating-3), but the NVP agents could also be considered instead of halon to inert the jet fuel or for micro-encapsulation (Rating-4). Another use of the NVP agents would be for local applications such as spraying at aircraft exit doorways for local protection for egress (Rating-3).

3.3 MODIFIED FUEL CONSUMED DURING FLIGHT

Reviews of past efforts on gelled fuel (Rating-5) have indicated that fuel compatibility problems are of grave concern and that other alternatives present significant but not almost-insurmountable problems. Primary problems with gelled fuel are with moving the fuel in the fuel system and also with dumping fuel. Modern science has also indicated that gelled fuel might be ignited easier and flame propagation may increase due to the lack of heat transfer into the normally liquid fuel surface-volume, which accepts heat and buoyancy causes circulation for heat distribution.

Another point to be noted is the lack of full-scale system analyses (performance, cost/benefit, R&M) before the large research effort and testing proceeds (Rating-2). Basic research of technical feasibility should immediately be followed by analyses for full-scale implementation. Pumpability and heat-transfer type of full-scale effects can be determined with isolated testing in the laboratory, as can be combustor nozzle tests. This laboratory information

can then be used for order-of-magnitude analyses of full-scale implementation (Rating-2). Such analyses, including cost/benefit, should be done early in the program and presented at meetings and hearings so that all parties, including the aircraft manufacturers and the public, sign up to the costs and difficulties before the program proceeds.

Classical emulsions consist of a discontinuous phase (the fuel) that is dispersed within a continuous phase (the emulsifying agent). Suspension of oil and water soon separates; but the emulsifying agent for an emulsion surrounds the fuel into droplets and fire safety is the result of interactions between the droplets. The increase in emulsion viscosity is evidence of the increased droplet interaction. The emulsion is in effect a protective packaging of the neat fuel on a minute scale. The packaged droplets are in contact with each other and, because of their small droplet size with inherent high surface curvature, they strongly resist deformation. This stiff emulsion prevents fuel splash and spreading, and the immiscible film of low flammability material surrounding the fuel droplets effectively reduces vapor release.

There are many new emulsifying agents that have never been evaluated for emulsions. The early evaluations of emulsions by the FAA produced problems similar to gels since stiff emulsions were similar in character to stiff gels. Although it is unknown how new and different emulsifiers will perform for thickening, pumping, coalescing, combustion, turbine, emissions, etc., there are so many available emulsifiers that reinvestigation is warranted at moderate level (Rating-2). It is not questioned whether a good thickening emulsifying agent can be found but rather if the operational characteristics of the thickened fuel can be designed for good functionality.

Vapor-phase inerting emulsions do not work like classical emulsions that surround the fuel and facilitate droplet interaction for thickening, but work by binding the fuel and agent, say water, together so that preferential evaporation of the additive occurs at the flame front. This evaporation then preferentially releases the additive agent so that released fuel vapor cannot sustain a flame. In the case of a water-fuel emulsion the water vapor dilutes the fuel vapor at the flame front below the lower flammability limit, that is, vapor phase inerting. The emulsified fuel that is spilled now resists ignition and burning, whether or not a cloud of burning fuel mist or fuel vapor occurs. So the fire-safe water-fuel emulsion resists burning primarily in the spilled pool phase, and somewhat resists ignition and burning in the mist phase. In the case of a suppressant emulsion a fire suppressant such as halon is added to the fuel to form a halon-fuel emulsion or mixture. The proper choice of volatility of the halon-type agent then allows preferential release of the halon at the flame front to actually cause fire suppression rather than dilution as with the vapor-phase inerting water-fuel emulsion.

The tradeoffs between the water-fuel type vapor-phase inerting emulsions and the halon-type vapor-phase inerting suppressant emulsions are many. The suppressant emulsion is more efficient since less of the more-effective halon is used compared to the water. However, halon-type agents are heavy so the weight penalty is not insignificant. The halon-type agents are costly and form acidic products. With respect to the inerting of all the fuel by using a large amount of halon-type agent (6% by volume) as previously mentioned, the suppressant emulsions do have the

advantage of using less weight (2% by volume) by concentrating the agent via preferential evaporation for local high efficiency with respect to the overall weight.

Emulsions should be considered either (a) on their own merit (Rating-2) or (b) in combination with anti-misting agents (Rating-3). Anti-misting agents are limited by working up to a certain range of shear and do not work when the fuel is hot so that fuel vapor can form. The use of an emulsion along with an anti-misting agent covers both fields, that is, prevent mist ignition and prevent pool burning. Additionally, synergism has been reported for the emulsion/anti-mist combination. The quantitative details for synergism and limits of applicability need to be determined (Rating-3).

The early research for fire-safe fuel produced the highly viscous gelled fuels of the 1970's, and although the fire reduction characteristics were good, the engine and aircraft fuel system and ground refueling system compatibility problems were severe. Then the anti-misting kerosene (AMK) fuel was developed consisting of a few-tenths percent of high molecular weight polymeric additive with viscosities approaching those of neat jet fuel. Test results indicated that the fire resistance characteristics of the AMK fuel was comparable to the earlier viscous gelled fuels. As a result of the apparent failure of the AMK during a full-scale aircraft crash test (the CID) the FAA program was dramatically reduced. The failure of the AMK was explained by CID test conditions that were beyond the capability of the AMK. That is, the involvement of the aircraft engine was not anticipated as well as a crash with aircraft yaw and perhaps effort should now be directed toward a better understanding of the fuel breakup and ignition/flame propagation mechanisms in crash environments.

It should be kept in mind that anti-mist additives attempt to prevent burning of the aircraft's total fuel load by preventing ignition of fuel mist generated when spilled fuel is exposed to high speed air shear. There is essentially no protection for burning of spilled fuel pooling on the ground near the aircraft. Some of the main problems later determined for the CID were that (a) abnormal recirculation zones were formed, (b) fuel was thrown into open volumes of the aircraft after a door broke, (c) the shearing was beyond the capability of the specific AMK, and (d) the effect of engine involvement was not anticipated.

The FAA concentrated feasibility efforts on the FM-9 additive in order that a demonstration flight and crash test could be completed by the end of 1984. The proprietary FM-9 additive was a high molecular-weight styrene-based hydrocarbon polymer that is dissolved in Jet A fuel using a glycol/amine carrier fluid. The phase of the program to identify, screen, and develop other promising alternate anti-misting fuel candidate was terminated because of budgetary reductions. Several surmountable problems with the FM-9 additive AMK were identified concerning degradation, degradation testing, water-induced precipitate (Jet A can hold about 90-ppm of dissolved water whereas FM-9 AMK can hold greater than 1300-ppm of dissolved water), thick film on AMK-wetted cold surfaces, heat transfer, precipitate/deposit produced by incompatibility with anti-icing additive, and other minor problems with engine ignition, engine emissions, and flow sensitive components.

The concept of anti-misting additives is feasible and research on anti-misting additives should be pursued (Rating-1). Shear-thinning and shear-thickening compounds should be considered. The problems with getting sufficient specific knowledge of additive performance and crash conditions for performance requirements can be surmounted. The type and availability of anti-misting agents is currently unknown. The selections in the various types of additives and modeling technologies has significantly improved. Advances in rheological tools have enhanced the capacity for designing effective fuel additives, although more remains to be done for rheological evaluations (Rating-3).

Derivatives of the FM-9 additive have been developed that show promise in providing fire resistance at much lower concentrations and significant improvements in dissolution characteristics have been reported. The lower concentration is expected to solve or mitigate many of the environmental and compatibility problems identified with the 0.3 percent FM-9 AMK evaluation. Polymers and surfactants may be useful for reducing fuel flammability, and, in addition to polymers previously in existence that were not evaluated, today even many more polymers and surfactants are available. In addition, more powerful computational capabilities offer possibilities for molecular modeling and polymer design that were not previously available. Very high molecular weight anti-mist additives have been identified and provide protection at significantly lower concentrations which may imply less compatibility problems.

3.4 POST-IMPACT FUEL FIRE CONTROL

The main goal of commercial-aviation fire-safe fuel is to protect passengers in the case of a survivable aircraft crash and permit them to egress safely. One previously evaluated concept was to protect the aircraft cabin interior via the use of a water mist protection system. Newer cabin materials are more resistant to fire, but this does not imply that they will not burn or yield toxic gases. In an effort to develop further improvements in post-crash fire survivability, the FAA conducted full-scale tests showing that a zoned cabin water spray system is effective, safe and practical; however, further implementation was discontinued after a cost/benefit analysis was used to judge that the cost was too high for the life saving capability. This is indicative why it is imperative that the cost/benefit analyses/judgements be promulgated early in the program before large-scale expenditures are incurred. It is thought that the costs will always be high for a fire-safe fuel, and, that if a fire-safe environment for survivable aircraft crashes is pursued diligently, the concept for cabin water mist should be re-visited (Rating-3).

Along similar lines for increasing passenger potential to escape safely, the concept of spraying a cooling or fire suppressing agent at and through exit doorways was conceived. In this concept (Rating-3) the exits for passengers would be provided with increased protection by using water, NVP agents or fire-suppressing and cooling foam. The agent would be sprayed around doorways and/or onto/under the escape slides for protection against spilled fuel. This is similar to interior cabin water mist protection system except that protection is now afforded to the aircraft escape paths.

Review has shown that there is a helicopter fire protection system that sprays a firefighting agent external to the helicopter upon a crash. This provides for local fire-safety for passenger safety and egress. It is known that the burn-through time for an aircraft's aluminum skin is just 20 to 60 seconds. Recent tests at the Air Force Academy using INTELAGARD's compressed air foam (CAF) backpack system with various foams showed that (a) with Aqueous Film Forming Foam (AFFF), which is the primary agent used at airports, the burn-through time for 1/8th inch thick aluminum with AFFF application against a Jet A fuel fire was less than one-minute whereas it was more than a few minutes (no burn-through) using CAF-generated protein foam, and (b) whereas the burn-back resistance for AFFF about 12-inches thick on Jet A fuel was less than one-half minute, the burn-back resistance for about 8-inches of CAF-generated protein foam was greater than 15-minutes. These data show that enhanced local protection is indeed available. The use of CAF-generated protein foam with a small on-board system such as an automated version of a backpack for escape slide protection is feasible (Rating-3).

3.5 OTHER CONCEPTS FOR FIRE SAFETY

Dry chemical powders are very effective fire suppressants. The smaller particle diameter has a higher fire extinguishing efficiency. Larger dry chemical diameters have always been used because of the manufacturing and caking problems with very small particle diameters. A new method of generating very small diameter dry chemical is the pyrotechnically generated aerosol (PGA). The extremely fine particulates are generated in-situ by a pyrotechnic composition whereby salt particulates are produced by condensation from the vapor phase. In application to aircraft post-crash fire prevention the PGAs could be distributed to concentrate the fire prevention agent near flammable interfaces, such as inaccessible volumes, and the PGAs could be self-activated by fire heat (Rating-4).

Solid propellant gas generators (SPGGs) are viable alternatives for in-flight fire suppression. SPGGs are a spin-off of automotive airbag technology and rely on the controlled burning of solid reactants to produce inert gases (H_2O , CO_2 , and N_2) at high temperature which make them effective fire suppressants. SPGG devices can be used in a stand-alone fashion or in hybrid systems whereby the SPGG is used to pressurize a liquid fire extinguishant such as H_2O . It is thought that SPGGs could be used for a variety of applications for aircraft fire protection (Rating-3), either alone or in hybrid as the driver for another agent. For examples, (a) located in not readily accessible compartments, (b) driver for the agent (NVP or CAF) used for aircraft emergency escape slide protection, (c) external spray around aircraft (like the Russian helicopter), (d) external spray around aircraft exits for personal protection against escaping when fire exists near exits, and (e) driving an internal aircraft water mist protection system.

Past and recent tests have shown that burn-through time of the aircraft aluminum skin is less than one minute. This means that passenger escape time is severely limited when the aircraft is exposed to a fire after a survivable airplane crash. A method to increase burn-through time is to coat the aircraft with fire protection material. One concept would be to use an intumescent paint coating on the interior or exterior of the aluminum aircraft skin, and another concept would be to

coat the skin with paint that contains micro-encapsulated protecting agent (Rating-4).

With the availability of many surfactants, new methods for enhancing fire protection and suppression of spilled fuel become available. One concept uses a surfactant, such as that used in AFFF to make "light water", along with a halon-type agent. It is only the upper layer of fuel that participates in the process of fire since the fuel must vaporize and mix with air to form a flammable mixture. Since the fuel below the surface does not initially participate, then it would seem more efficient to only isolate or inert the fuel surface layer. The use of a specifically-selected surfactant with a halon-type agent would allow the projection of the halon-surfactant mix onto a burning fuel surface to cause efficient utilization of the halon at the fuel surface to cause extinguishment or inerting of the fuel surface. This is somewhat akin to forming a halon emulsion in-situ at the surface of the fuel, thereby achieving high efficiency of the agent (Rating-4).

Surrounding the fuel cell with a liquid or gaseous inhibitor via a co-annular tank or surrounding the fuel tank with dry chemical panels may offer protection for combat vehicles but appear to offer only limited protection for commercial aircraft. Separation of a fire-prevention additive before the fuel goes to the engine for combustion has never been demonstrated; however, it seems feasible and should be kept in mind when evaluating potential concepts.

Anti-misting agents show no effect on flame propagation over fuel spills for either low or high flash point temperature fuels once the pool fire is initiated. For high flash point fuels, pool fire initiation can be prevented by using anti-misting agents to inhibit or eliminate the occurrence of a fire ball. Therefore, if only an anti-misting agent is to be used then assurance must be provided that other fuels and ignition sources other than a potential fire ball are eliminated.

It has been suggested that another class of polymers, so-called "association polymers", might be substituted for the material conventionally used as anti-misting agent to eliminate the shear degradation problem. In this type of polymer, a very high molecular weight is achieved by linking smaller polymer units, which are not shear degraded, by means of hydrogen or ionic bonds. The assumption here is that, while shear might temporarily disrupt the bonds, the bonding would reform rapidly. Critical points in judging the utility of such compounds, if they do exist, would be the determination of the range of shear energy under which the bonding would be destroyed (without destroying the bonding of the smaller polymer units) and the time required for the association bonding to reform. For the polymer to be effective, it would likely have to have re-association times the order of milliseconds, if not microseconds, and such short association times might interfere with fuel injection atomization. The possibility of the future use of association polymers is considered to be highly speculative (Rating-4).

REFERENCES

Bannister, W.W. and et.al., A Non-Volatile Precursors to Alternative Halon Fire Extinguishing Agents with Reduced Global Environmental Impacts, @ Department of Chemistry, University of

Massachusetts, Lowell, MA 01854, Proceedings of the 1993 International CFC and Halon Alternatives Conference, P.O. Box 236, Frederick, MD 21701, 301/695-3762, pages 761 - 766

Kahn, S.A., Royer, J.R., and Srinivasa, R.R., ARheology: Tools and Methods, @ Aviation Fuels with Improved Fire Safety - A Proceedings, National Materials Advisory Board of the National Research Council, National Academy Press, NMAB-490, Washington, DC, 1997 pages 31-46.

McCourt, F.P., AUS Army Fire Hazard R&D Activity, @ Aircraft Fluids Fire Hazard Symposium, The Daniel & Florence Guggenheim Aviation Safety Center at Cornell University, 470 Park Avenue South, New York, NY 10016, 1966 Proceedings, pages 56-61.

Miller, R.E., ASafety Fuel Research in the United Kingdom, @ AGARD Conference Proceedings No. 166 on Aircraft Fire Safety, AGARD-CP-166, Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organization, 7 rue Ancelle, 92200 Neuilly sur Seine, France, October 1975, pages 1-1 to 1-10.

Taylor, W.F., AJet Fuel Chemistry and Formulation, @ Aviation Fuels with Improved Fire Safety - A Proceedings, National Materials Advisory Board of the National Research Council, National Academy Press, NMAB-490, Washington, DC, 1997 pages 47-52.

Weatherford, W.D. and Wright, B.R., AStatus of Research on Antimist Turbine Engine Fuels in the United States, @ AGARD Conference Proceedings No. 166 on Aircraft Fire Safety, AGARD-CP-166, Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organization, 7 rue Ancelle, 92200 Neuilly sur Seine, France, October 1975, pages 2-1 to 2-12.

Zallen, D.M., AHalon Replacements Study - Final Report, @ Report No. ZIA-94-0100, July 1994, for Air Force Materiel Command, Aeronautical Systems Center, Wright-Patterson AFB, OH.